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Storm Enhanced Bottom Shear Stress and Associated Sediment Entrainment in a Moderate Energetic Estuary

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Several important mechanisms for storm-induced entrainment of estuarine cohesive sediments are analyzed using field measurements collected in a moderately energetic estuary, central Long Island Sound, U.S.A. The sediment concentration and hydrographic data were obtained by an array of sensors mounted at 1 m above the bottom. The bottom sediment in the study site composed mostly of silt and silty sand. The study showed that the bottom shear stress, computed using a wave-current interaction model, increased significantly during the episodic wind events. A large resuspension event was triggered by a frontal passage when strong wind-driven currents augmented the tidal currents. The timing of storm waves with respect to the tidal phase also was a critical factor. Based on the changes of suspended sediment concentration, the bottom appeared to respond to the shear stress in two phases: the tidal resuspension and the storm-induced erosion. During each tidal cycle, entrainment was associated with resuspension of high water content, loosely consolidated material. During episodic events, a thin layer of more consolidated bed below the sediment-water interface was eroded by the enhanced bottom stress.

Keywords:
· Storm,
· shear stress,
· cohesive sediment,
· erosion,
· estuary.

1. Introduction

The entrainment of estuarine cohesive sediment has been a subject of intensive research in recent years. An important reason is that movement of the cohesive sediment is related to the redistribution of nutrients, heavy metals, and contaminated materials. The sediment movement is affected by the waves, currents, the saline and thermal conditions, and the biogeochemical factors (Mehta, 1989). In most estuaries the astronomical tide, with different constituents, is the primary factor governing the near-bottom suspended sediment concentration. For example, Allen *et al*. (1979) showed that a large amount of fine sediments was alternately eroded, resuspended and deposited during each semi-diurnal tidal cycle. Gelfenbaum (1983) reported that sediments were resuspended and advected by the semi-diurnal tide.

In addition to the tidal force, the near-bottom shear stress induced by surface waves makes up the basic driving force for the resuspension and subsequent distribution of the fine sediments. A field observation of surface wind and wave induced erosion was carried out by Lesht *et al*. (1980), who showed that the concentration was proportional to the wave orbital velocity when the velocity was above a threshold value (approximately 20 cm/s). Ward (1985) reported that the wind waves frequently resuspended significant amounts of sediment in shallow near-shore area in the middle Chesapeake Bay. Butman (1987) showed that, on the Georges Bank and in the Middle Atlantic Bight, bottom sediments were rapidly reworked and resuspended during the passage of storms. The sediment resuspension was primarily caused by increase of the bottom oscillatory currents associated with surface waves. In central Long Island Sound (LIS), Bedford *et al*. (1987) demonstrated that the sediment entrainment fluxes were correlated with the turbulent and wave kinetic energy. In the same area, Bohlen (1987) also reported disturbances of the sediment-water interface due to aperiodic, high-energy wind events. The strength of the sediment resuspension was governed primarily by the storm duration and directionality.

The sediment resuspension and bottom erosion are further enhanced by interaction between waves and currents (Grant and Madsen, 1979). Drake and Cacchione (1986) and Lyne *et al*. (1990) reported that combination of storm waves and wind-forced currents produced large sediment resuspension. In this paper, we described a study

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of the combined effects of currents, waves, and wave-current interaction on sediment suspension and erosion in a moderately energetic estuary. Factors governing the storm-enhanced bottom shear stress and the associated sediment resuspension were analyzed using *in-situ* measurements over a two-week period covering a wide range of hydrodynamic conditions. Particular attention was placed on the effects due to passage of storms in relation to the local geography and current system.

2. Field Observations

The field data were collected in central Long Island Sound (Fig. 1(a)) during the period of 29 November to 15 December 1983. This study was a cooperative project consisting of several research groups to monitor the impact of dredged materials near a disposal site (SAIC, 1984). The average water depth was 20 m with the sea bed gradually descending southward. The surficial layer of the bed was mostly covered by fine grain sediments, because of the accumulation of disposed dredged material. Analysis of surface sediment samples in the vicinity of the study area indicated that mixtures of the silt and silty sand made up about 92% of the bottom content (SAIC, 1990). The bottom characteristic of the study area was considered to be very cohesive and uniform over spatial scales of half of a tidal excursion distance, which was about 6 km (Fig. 1(b)).

Hydrographic and suspended sediment data were collected from a bottom mounted instrument array with sensors positioned at 1 m above the bottom. The array was equipped with a Marsh-McBirney two-axes electromagnetic current meter, a compass, two water temperature sensors, a SeaBird Electronics Model-4 conductivity probe, and two red-light transmissometers with a 10-cm path length. The instrument array was controlled by a digital data logger. The array was calibrated prior to the deployment, and the procedures were reported in Bohlen (1982). The data logger was programmed to sample every 15 min for a duration of 96 s at a sampling frequency of 0.5 Hz. Also, a Paroscientific digital quartz pressure sensor attached to the frame was used to record bottom pressure. A separate data logger was provided for the storage of pressure measurements. The wave gauge was programmed to sample at a frequency of 1 Hz for a period of

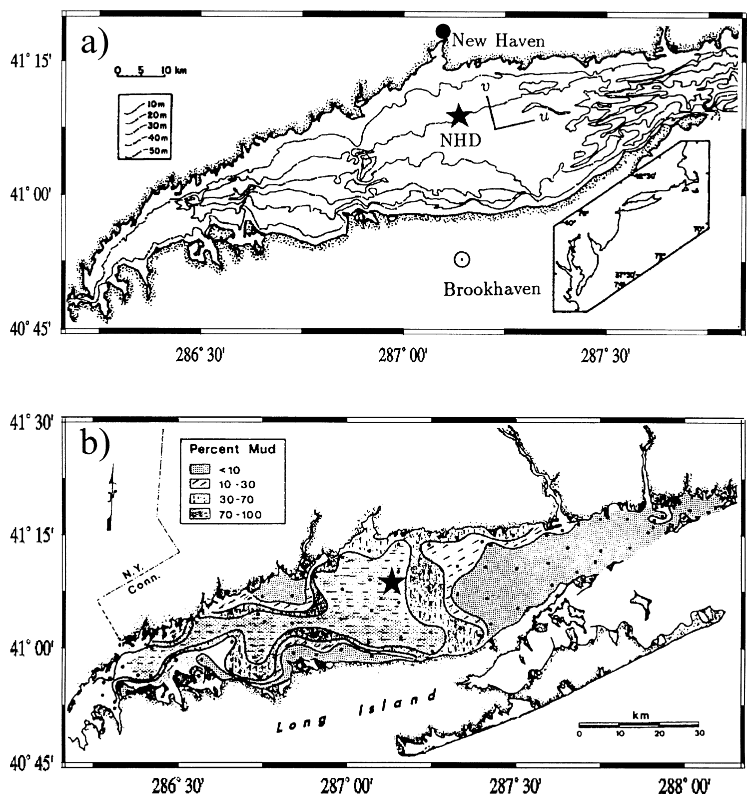

Fig. 1. Maps: (a) depth contours (from Bokuniewicz and Gordon, 1980) and (b) sediment patterns in the Long Island Sound (from Wakeland, 1979). The instrumentation site, NHD (★) is located in a 20 m water of an essentially uniform bottom. The bed sediments are mostly composed of silt and silty sand. The meteorological station (⊙) is located about 30 km south of the study site.

512 s every 30 min. Tidal heights were also recorded every 15 min by the wave guage. In addition, meteorological data were obtained from Brookhaven National Laboratory in Upton, New York, a land station located about 30 km south of the study site (Fig. 1(a)). Winds at 97 m were used to derive the 10 m wind according to the procedure of Blanton *et al*. (1989). The computed wind velocities at 10 m were about 84% of the measurements. The time interval of wind data was 60 min.

3. Data Analysis

The procedures used to process the hydrographic and suspended sediment measurements were similar to those of Cacchione and Drake (1982). Mean values of current velocity, temperature (T) and sediment concentration (C) were computed within each burst. In order to examine the effect of local geometry on the current, the resulting current velocities, along with winds, were rotated to the principal axis coordinates, which at this site were along (u) and across (v) the isobath (Fig. 1). To identify the low frequency forcing, a Fast Fourier Transform (FFT) low-pass filter of Walters and Heston (1982) was applied to the current and tidal data with a cutoff period of 30 hr. Cross-correlation analysis was applied to the time series of sediment and hydrographic data.

Wave period and wave height were derived from the bottom pressure measurements using basic linear wave theory (Kinsman, 1965). The pressure gauge recorded 512 samples (one per second) every 30 min. Prior to the wave computation, preliminary data processing was carried out to exclude the outliners. Those data points that fell outside the range of two standard deviations were replaced by the mean value within the burst. Each burst of data was converted to surface wave heights, which were then demeaned and detrended to remove the low frequency components such as those due to tides. A FFT was applied to each burst of data to obtain energy spectrum. The frequency at the peak of the spectrum was used to determine the significant wave period (T_s). A verification calculation found this method yielded results almost identical to the significant wave period computed by the zero up-crossing method. The significant wave height (H_s) was estimated using four times the standard deviation of the spectrum energy of surface waves (Kinsman, 1965). Wavelength (L) can be derived using the dispersion equation:

$$L \approx \frac{gT_s^2}{2\pi}\sqrt{\tanh\frac{4\pi^2}{T_s^2}\frac{h}{g}}, \tag{1}$$

which is correct to within about 5% (U.S. Army Corps of Engr., 1984). The computed results showed that the estimated wave periods ranged mostly from 4 to 8 s with associated wave lengths of about 26 to 100 m. This indicated that the maximum orbital velocity (u_b), in 20 m of water, can be related to H_s, T_s and L using

$$u_b = \frac{\pi H_s}{T_s} \bigg/ \sinh\frac{2\pi h}{L}. \tag{2}$$

The bottom shear stress was computed based on the current and wave data using Grant-Madsen model (Grant and Madsen, 1979). Five parameters were used in an iterative procedure including maximum wave orbital velocity (u_b), wave frequency ($\omega = 2\pi/T_s$), current velocity at a known distance above the bottom (u_c), angle between current direction and wave direction (ϕ_{cw}), and bottom roughness (z_0). In this study, u_c, u_b, and ω were supplied by the field measurements. The bottom roughness was chosen to be 0.1 cm (Grant *et al.*, 1984). Previous studies showed that the shear stress computation was relatively insensitive to the value of z_0 (Drake and Cacchione, 1986). To specify ϕ_{cw} without the wave directional spectrum, the wave direction was assumed to be in the prevailing wind direction, and the angle between wave direction and current direction was determined. This approach was justified, since in this study during storms the prevailing winds were in the along-channel direction and the ϕ_{cw} was assumed to be zero.

4. Results

Figure 2 depicts the computed current velocities, wave orbital velocity, total shear stress under wave-current interaction (τ_{cw}), suspended sediment concentration and water temperature. The currents fluctuated on semi-diurnal tidal frequency. The daily maximum current velocity ranged from 20 to 40 cm/s. The along-channel current was much greater than the cross-channel velocity, revealing the rectilinear nature of the tidal current. There were four meteorological events that can be clearly identified from the wave data. For convenience of discussion, these four storm events were denoted as E1, E2, E3, and E4. At a depth of 20 m, the maximum bottom wave orbital velocity varied from 10 to 25 cm/s during storms, and was almost zero during calm weather. Each of these large wave events lasted for 1–2 days. The growth and decay of each event was different. For example, event E3 grew rapidly to its peak value and decayed slowly. Event E2 had a sharp peak while E3 had a longer duration of large waves. The current velocities during events were stronger than during the normal days. In particular, there were two large ebbing currents during event E3. The resulting total bottom shear stress had an average peak value of approximately 3 dyn/cm^2. Shear stress significantly increased during the four events, and the values of peak shear stress ranged from 15 to 36 dyn/cm^2. During these

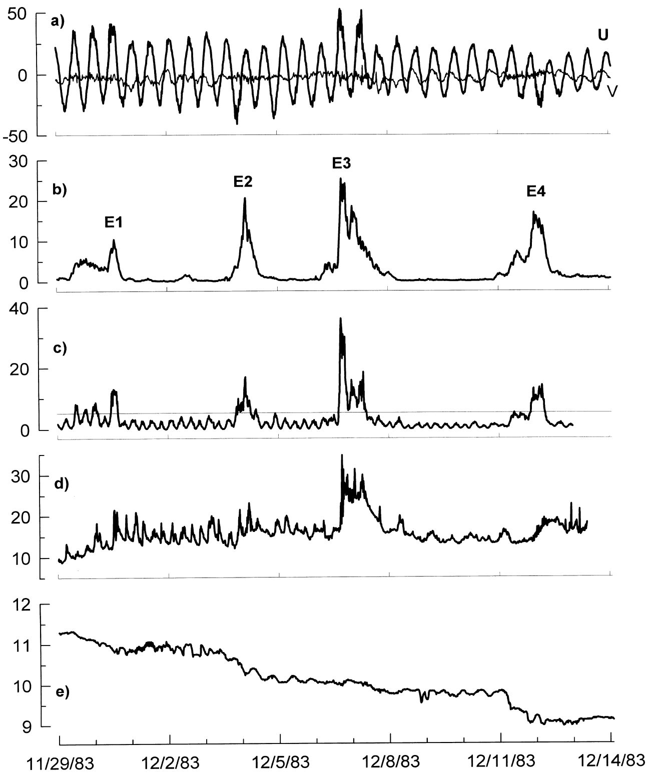

Fig. 2. Time series of (a) current velocities (cm/s), (b) wave orbital velocity (cm/s), (c) total bottom shear stress (dyn/cm^2), (d) suspended sediment concentration (mg/l) and (e) water temperature (°C). Four meteorological events, E1, E2, E3, E4, are marked.

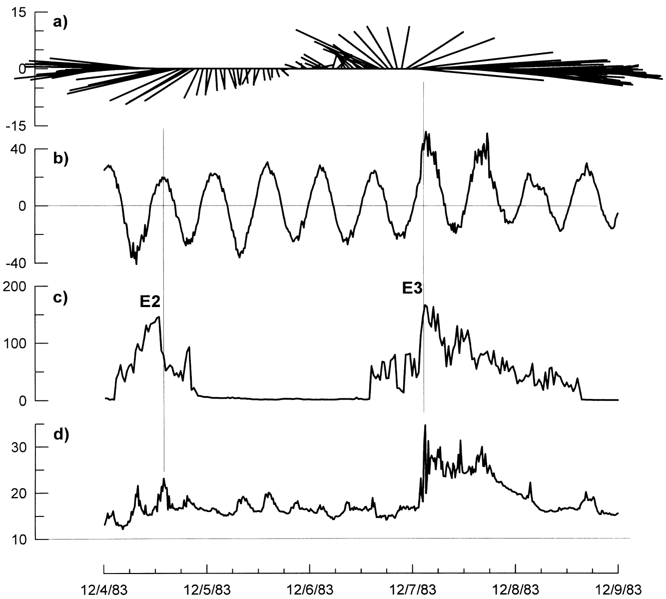

Fig. 3. (a) Stick diagram of 10 m wind (m/s), (b) along-channel current (cm/s), (positive is seaward), (c) significant wave height (cm), and (d) suspended sediment concentration (mg/l), during a 5 days period including the E2 and E3 events.

events, the wave-current interaction significantly increased the computed bottom shear stress. The currents and waves tended to enhance each other that the shear stresses during the peaks of storms, computed from the wave-current interaction model, were approximately 3 times larger than using the traditional quadratic law. These results agreed with Lyne *et al*. (1990) who showed that the bottom stress calculated using Grant-Madsen model exceeded the stress computed from the conventional drag law by a factor of about 1.5 on average and 3 or more during storm peaks.

Suspended sediment concentrations ranged between 10 and 35 mg/l. Typically, the suspended sediment concentrations fluctuated with a magnitude of 10 mg/l or less. The fluctuations of suspended sediment concentration, in general, were in phase with the shear stress. There were four peaks of concentration and shear stress per day, which indicated that these fluctuations were dominated by semi-diurnal tide. Besides the normal tidal variations, the suspended sediment concentration was affected by the high shear stress events. There were a large increase in concentration at E3 and smaller increases during events E1, E2 and E4. During the three small events, the shear stresses increased substantially, but there was only a slight increase in suspended sediment concentration compared to the non-storm periods. During the major resuspension event E3, the shear stress increased from an ambient value of 3 dyn/cm^2 to a peak of 36 dyn/cm^2, and the suspended sediment concentration increased from a background value of 15 mg/l to a maximum of 35 mg/l.

Water temperatures progressively dropped from 10 to 8°C during the two-week period. The atmospheric temperature was below 10°C most of the time, and the mean air temperature was 5°C. The low air temperature favored cooling of the water column because of the negative surface heat flux. Also, the water temperature displayed a weak tidal signal with amplitude of less than 0.5°C. The small temperature variation at tidal frequency and the progressive decrease in water temperature suggested that the water column was almost homogeneous in the vertical. The absence of stratification favored the vertical transfer of surface wind energy, which enhanced the bottom shear stress, erosion, and near-bottom mixing.

Of these four events, the peak bottom shear stress at E3 was significantly higher than the other three. The cause of the large increase in shear stress was further explored by examining the characteristics of wind, wave, and current. The wave orbital velocity substantially increased during all four events. In particular, the maximum wave orbital velocity of E2 was similar to that of E3. This suggested that besides large waves, the magnitude of bottom

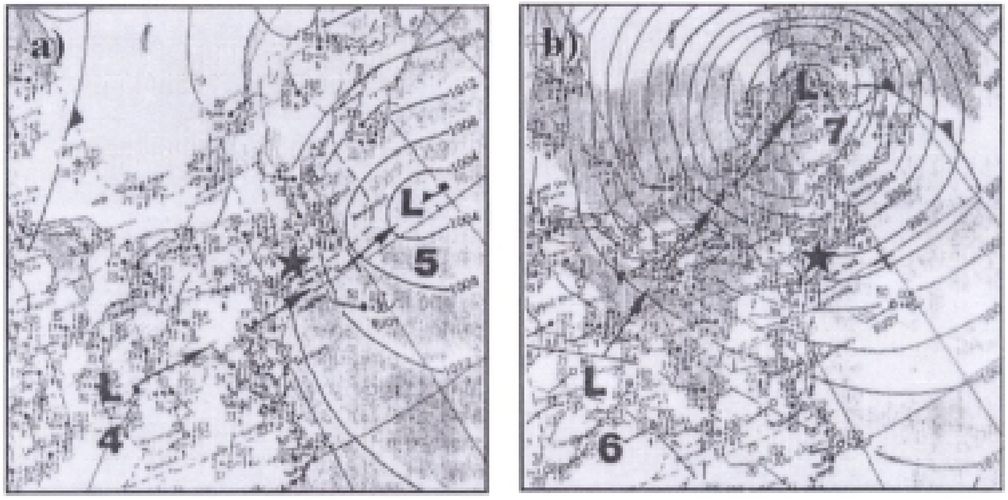

Fig. 4. Daily weather maps: (a) a winter front passed south of the study site on December 5, and (b) a stronger front passed north of the study site on December 7, 1983.

current was important to the sharp increase in shear stress at E3. To substantiate this finding, the wind and current during E2 and E3 were examined in more details to study the mechanism causing large bottom shear stress during E3. Figure 3 showed that E2 took place when the westward wind was superimposed on an eastward tidal current. In contrast, E3 occurred when both wind and current were in the eastward (seaward) direction. In other words, during E3, the eastward wind-driven current augmented the tidal current, which together with large waves, caused a strong bottom shear stress. It should be noticed that at 6 hours prior to E2, the westward wind was in the same direction as the flooding tidal current, and the total velocity was enhanced. However, since the storm waves were not yet fully developed, the resulting shear stress was smaller than that of E2 or E3. Therefore, the timing of high waves relative to strong current was also critical.

The winds during E2 and E3 were due to the passage of frontal systems (Fig. 4). On December 4 (E2), winds were from the southeast, due to a low pressure system moving in from the southwest of Long Island Sound (LIS) on a northeast course. The center of the low passed south of LIS and the winds shifted to northeasterly on December 5. Another intense low-pressure system developed on December 6 (E3). While this system was in the southwest of LIS, a southerly wind was observed. The center of this low passed north of LIS on December 7 heading to the northeast. The winds shifted from the southwesterly to the westerly then to the northwesterly.

5. Discussion

The erosion occurs when the shear stress at cohesive bed overcomes the inter-particle attractive force or the shear strength of sediment column, and the bed erodes to a depth at which the fluid shear stress corresponds to the bed strength (Krone, 1962). During the non-storm period, coherent fluctuations of sediment concentration and shear stress suggested that there was a layer of high water content surface fluffy material being alternately resuspended and deposited throughout the tidal cycle. The fluffy layer was resuspended in the water column when the current velocity increased, and settled down when the current slackened. Beneath fluffy layer a thin layer of bottom sediment could be eroded to cause large increase in the suspended sediment concentration. This layer apparently was very stable, since there were only small increases in suspended sediment concentrations during E1, E2 and E4. Furthermore, the magnitude of suspended sediment concentration fluctuation after the storm event was much smaller than before the event (Fig. 2), suggesting that less bed sediment material was available after storm for resuspension. On the other hand, during the E3 event, apparently a layer of bed material was eroded, resuspended and swept away by the strong storm-enhanced currents, and afterward, the bottom was covered with a thin layer of newly deposited, loosely consolidated sediment. The amount of material eroded in E3 can be estimated by the increment in suspended material concentration. The sediment concentration increased from 15 to 35 mg/l during the event. Assuming that there was a 20 mg/l increase in sediment concentration, the total increase in suspended sediment mass was 0.04 g/cm^2 over a 20 m water column. This mass could be supplied by erosion of 0.36 mm of the bed with a sediment density of 1.1 g/cm^3 (a value close to the density of high water content sediment).

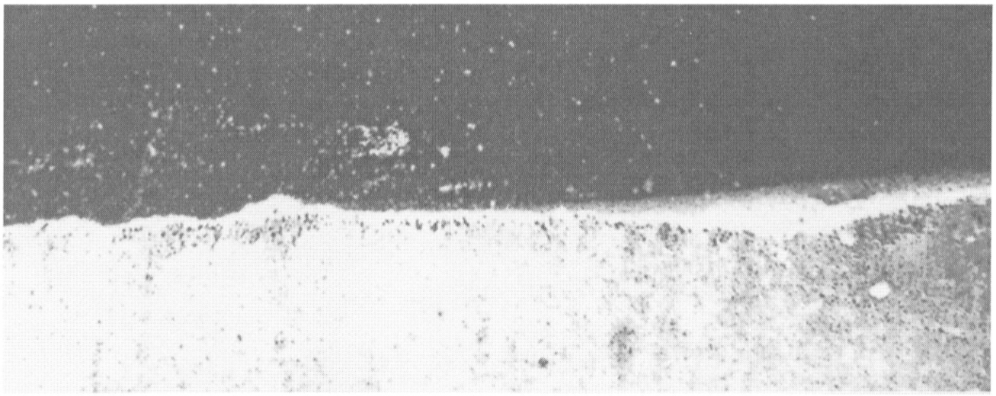

Fig. 5. A typical example of REMOTS photograph obtained in the vicinity of the study site on 24 January 1984. A thin layer of surface soft mud can be identified lying on top of a more consolidated materials. Scale = 1×. (Provided by SAIC, Newport, R.I., U.S.A.)

Our observations were consistent with the previous studies of sediment structure in the central LIS using REMOTS (SAIC, 1984, 1990), a device designed to take photograph while cutting through the sediment-water interface. These REMOTS photographs showed that there was an increase in the degree of sediment consolidation with depth. Typically, as shown in Fig. 5, a thin layer of loosely consolidated fluffy material overlies a more consolidated bed. The thickness of the fluff was of the order of 1 mm. It is also useful to compare our observations with sediment erosion model. For example, a multi-layer bed model is used in Parmeshwar *et al*. (1996). In their San Francisco Bay study, the erosion process proceeds downward through layers of original bed so long as the imposed shear stress exceeds the critical shear stress at each erodible layer. Their erosion bed model is similar to the erosion behavior in our study. In contrast, in Govindaraju *et al*. (1999), the bed is treated as a continuum, and a small portion of the hard bed underneath is susceptible to erosion in each tidal cycle. Govindaraju *et al*. (1999) assume that the shear stress is of the order of 100 dyn/cm^2 and the erodible sediment bed is of the order of 1 m. In central LIS, the erodible bed is only 1 mm in thick and the maximum shear stress is 40 dyn/cm^2.

The time series data showed that the sediment concentration was related to the current speed. It would be desirable to develop an erosion rate formula using *in-situ* measurements such as in Lavelle *et al*. (1984). However, simple statistical analysis showed that the cross-correlation coefficient was small, about 0.3, between the sediment concentration and bottom shear stress. The correlation improved slightly (0.35) when the shear stress was led by 15 min. The poor correlation was likely due to the fact that there were many factors, including the ambient concentration, settling of sediment, and stress history of sediment bed, which affected the sediment concentration. For example, the antecedent condition of a sediment bed could be important to the next resuspension event, and the high sediment concentration could occur during low current speed due to settling of sediment in the lower water column. The present study did not have all the relevant information to develop a robust formula for erosion rate in shallow water environment.

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References

Allen, G. P., J. C. Salomon, P. Bassoullet, Y. Du Penhoat and C. De Grandpre (1979): Effects of tides on mixing and suspended sediment transport in macrotidal estuaries. *Sed. Geol.*, **26**, 69–90.

Bedford, K., O. Wai, C. Libicki and R. Van Evra, III (1987): Sediment entrainment and deposition measurements in Long Island Sound. *ASCE, J. Hydr. Engr*., **113**, 1325–1342.

Blanton, J. O., J. A. Amft and D. A. Lee (1989): Wind stress and heat fluxes observed during winter and spring 1986. *J. Geophys. Res*., **94**, 10686–10698.

Bohlen, W. F. (1982): In-situ monitoring of sediment resuspension in the vicinity of active dredge spoils disposal areas. *IEEE Oceans '82 Proc*., 1028–1033, New York, N.Y.

Bohlen, W. F. (1987): Time variability of suspended material concentrations in estuaries. *Proc. 1987 Natl. Conf. Hydr. Engr., ASCE J. Hydr. Div*., 219–224, Williamsburg, V.A.

Bokuniewicz, H. J. and R. B. Gordon (1980): Sediment transport and deposition in Long Island Sound. p. 69–106. In *Advances in Geophysics 22*, ed. by B. Saltzman, Academic Press, London.

Butman, B. (1987): Physical processes causing surficial-sediment movement. p. 147–162. In *Georges Bank*, ed. by R. H. Backus and D. W. Bourne, The MIT Press, Cambridge, Mass.

Cacchione, D. A. and D. Drake (1982): Measurements of storm-generated bottom stresses on the continental shelf. *J. Geophys. Res*., **87**, 1952–1960.

Drake, D. E. and D. A. Cacchione (1986): Field observations of bed shear stress and sediment resuspension on continental shelves, Alaska and California. *Cont. Shelf Res.*, **6**, 415–429.

Gelfenbaum, G. (1983): Suspended-sediment response to semidiurnal and fortnightly tidal variations in a mesotidal estuary, Columbia River, U.S.A. *Mar. Geol.*, **52**, 39–57.

Govindaraju, R. S., S. R. Ramireddygari, P. L. Shrestha and L. C. Roig (1999): Continuum bed model for estuarine sediments based on nonlinear consolidation theory. *J. Hydr. Engr*., **125**, 300–304.

Grant, W. D. and O. S. Madsen (1979): Combined wave and current interaction with a rough bottom. *J. Geophys. Res*., **84**, 1797–1808.

Grant, W. D., A. J. Williams, 3rd and S. M. Glenn (1984): Bottom stress estimates and their prediction on the Northern California Continental Shelf during CODE-1: the importance of wave-current interactions. *J. Phys. Oceanogr*., **14**, 506–527.

Kinsman, B. (1965): *Wind Waves*. Prentice-Hall, Englewood Cliffs, N.J., 676 pp.

Krone, R. B. (1962): Flume studies of transport of sediment in estuarial shoaling processes. Final Report, Hydr. Engr. and Sanitary Engr. Res. Lab., Univ. of California, Berkeley, C.A.

Lavelle, J. W., H. O. Mofjeld and E. T. Baker (1984): An in-situ erosion rate for a fine-grained marine sediment. *J. Geophys. Res*., **89**, 6543–6552.

Lesht, B. M., T. L. Clark, R. A. Young, D. J. P. Swift and G. L. Freeland (1980): An empirical relationship between the concentration of resuspended sediment and near-bottom wave-orbital velocity. *Geophys. Res. Lett*., **7**, 1049–1052.

Lyne, V. D., B. Butman and W. D. Grant (1990): Sediment movement along the U.S. east continental shelf—I, Estimates of bottom stress using the Grant-Madsen model and near-bottom wave and current measurements. *Cont. Shelf Res*., **10**, 397–428.

Mehta, A. J. (1989): On estuarine cohesive sediment suspension behavior. *J. Geophys. Res*., **94**, 14303–14314.

Parmeshwar, L., P. L. Shrestha and G. T. Orlob (1996): Multiphase distribution of cohesive sediments and heavy metals in estuarine systems. *J. Env. Engr*., **122**(8), 730–740.

SAIC (1984): Results of monitoring studies at cap site #1, #2, and the FVP site in central Long Island Sound and a classification scheme for the management of capping procedures. DAMOS Contribution #38, SAIC, Newport, R.I.

SAIC (1990): Disposal area monitoring system progress report. DAMOS Contribution #68, SAIC, Newport, R.I.

U.S. Army Corps of Engr. (1984): Shore Protection Manual. U.S. Army Engr. Waterways Exp. Stn., Vicksburg, Mississippi, Government Printing Office, Washington, D.C.

Wakeland, M. E., Jr. (1979): Provenance and dispersal patterns of fine-grained sediments in Long Island Sound. Ph.D. Dissertation, Univ. of Connecticut, Storrs, C.T.

Walters, J. T. and C. Heston (1982): Removing tidal-period variations from time-series data using low-pass digital filters. *J. Phys. Oceanogr*., **12**, 112–115.

Ward, L. G. (1985): The influence of wind waves and tidal current on sediment resuspension in middle Chesapeake Bay. *Geo-Marine Letters*, **5**, 71–75.